

The Military Emergency Tourniquet Program's Lessons Learned With Devices and Designs

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ABSTRACT Objective: The purpose of this study is to report the device lessons learned from an emergency tourniquet program and, in particular, to emphasize analysis of discarded devices recovered after clinical use. Methods: Discarded tourniquet devices were analyzed after use in emergency care of war casualties to determine wear and tear patterns, effectiveness rates, and associations among device designs. Results: The 159 devices recovered comprised seven designs. Emergency & Military Tourniquet (92%) and Combat Application Tourniquet (79%) effectiveness rates were significantly different from each other and better than other tourniquets ($p < 0.002$) as the most effective ambulance and field tourniquets, respectively. Designs had specific pitfalls (e.g., sand-clogged ratchets) and strengths (the pneumatic design was least painful). Every device had wear, abrasions, or deformity about the band edges or bladder. User understanding of how devices work best helped attain better results. Some desirable traits (e.g., one-handed application, use for entrapped limbs) were rarely needed. Tourniquets fit casualty limbs well. Conclusions: Correct user actions (e.g., following the instructions to remove slack before twisting) led to device effectiveness, but misuse did not. Users often assumed that optimal use required more force, but this was associated with misuse. Training should include tourniquet pearls and pitfalls.

INTRODUCTION

Emergency tourniquet use is lifesaving with minor morbidity if the right devices are used at the right time for the right casualties in the right way.¹ These four issues have been studied in prior reports; but of these the right device is least understood, and evidence in actual use is lacking.² Also from one of these reports, preliminary data indicate that use and misuse affect device performance and clinical outcome.² Common guid-

ance not based on data said that rope or wire is to be used to improvise strap-and-stick tourniquets,³ but new data indicate that improvised devices are inferior to well-designed devices.² For the first time, the U.S. Department of Defense systematically collected prehospital and emergency department (ED) data on tourniquets. The purpose of this report is to fill the specific knowledge gap on device performance by reporting the experience of the U.S. Army Institute of Surgical Research (USAISR) in that program.

The tourniquet program's cornerstone was a clinical investigation at a combat support hospital in Baghdad. The program was supervised by a team of emergency tourniquet experts at the USAISR at Fort Sam Houston, Texas.^{1,2} The program's clinical trial offered an opportunity to collect discarded devices after use for analysis by experts to better understand how devices were used. Specifically, the team focused on the association of design and device wear with clinical effectiveness. The investigators collected devices and gathered experience with many designs which supplemented knowledge from comparative testing and consultations with users and manufacturers.^{1,2}

The aim of this study is to report emergency tourniquet device lessons learned from a large emergency tourniquet program and, in particular, to analyze devices recovered after clinical use.

MATERIALS AND METHODS

This report of the experience of the Department of Defense's Emergency Tourniquet Program is based primarily on data derived from a research project at Ibn Sina Hospital in Baghdad

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(National Clinical Trial NCT00517166 at ClinicalTrials.gov).^{1,2} The program leader was an orthopedist assigned to the USAISR (protocol I.2006.175dt approved by the institutional review board, Tables I-IV). This study was conducted under a protocol reviewed and approved by the Brooke Army Medical Center Institutional Review Board and in accordance with good clinical practices. After emergency casualty care was complete, tourniquet users decided when to discard devices in the normal course of care. Since there was an epidemic of casualties, the investigators, who were also the stewards of the hospital's tourniquet care program, returned some devices to use in the ED.

The investigators collected discarded tourniquets and sent them to the USAISR for analysis. They recorded where on the device wear occurred, where it was minimal or absent, when wear occurred, and what was associated with wear (particularly actions that led to device deformity and breakage). When possible, wear and tear was associated with clinical data from

our USAISR clinical reports as some devices had care data written on them, attached to them, or associated with them.^{1,2} Effectiveness data came from this study data, but we also put that data in context of the clinical report data which we additionally analyzed statistically for performance by make (including improvised tourniquets). Effectiveness as defined and collected in the earlier report entailed looking at effectiveness in two ways, (1) did the tourniquet stop the bleeding, and (2) if it stopped the distal pulse; in other words, was the tourniquet fully or partially effective.² Effectiveness by individual device was yes/no and was summarized by tourniquet make as a proportion to compare with other makes. Since the most could be learned from devices that had the most extreme problems compared to devices with routine performance, the investigators were most interested in device performance that was unusual (e.g., when they broke). Nonfunctional was defined in that the device did not function to stop the distal pulse as in a normal volunteer irrespective of cause such as breakage or scissoring. Deformation in the device that remained observable was evidence of use (e.g., devices had maximal inner strap deformation where the outer band also had its maximal deformation and also where the touching windlass had its maximal deformation).

The investigators used descriptive statistics to describe device traits and effectiveness rates. They outlined tourniquet effectiveness previously by survival rate and other outcomes, but here effectiveness means stopping the distal pulse.^{1,2} Safety was addressed previously.²

TABLE I. Functions of the U.S. Department of Defense Emergency Tourniquet Program

- Produce papers and knowledge products like the current work on recovered devices
- Test unused devices and assessing devices in comparison of available competitors
- Conduct market surveillance for emerging technologies and analyzing items periodically
- Consult with manufacturers, trainers, allied providers, and doctrinaires
- Recommend doctrine refinements with doctrinaires
- Recommend refinement of designs with engineers, manufacturers, and inventors
- Review designs in patent applications
- Consult with other organizations (logisticians, academicians, contract representatives, publishers, military units, medical professional organizations, emergency service stakeholders)
- Facilitate investigations, such as death reviews, with inspectors general
- Testing and analyze used and recovered devices for performance improvements or redesign
- Conduct clinical trials when indicated
- Act as subject matter experts for foreign and domestic military services

TABLE II. Emergency Tourniquet Use Settings

Setting	Principal Users
Field	Lay person, junior medic
Casualty collection point	Junior medic, senior medic
Ambulance (ground or air)	Medic, paramedic
Clinics	Medic, physician assistant, nurse, physician
ED, hospital	Medic, nurse, physician, surgeon

For the latter settings, the supervisors often instruct medics and nurses to apply the devices.

RESULTS

Recovered devices numbered 159 in this study (8 were improvised and 151 were commercially designed as tourniquets, Table V). Of the 159, 110 were still functional, and 49 were damaged to the point of being nonfunctional. Devices were nonfunctional because they had a loose or lost securing strap (15), were cut off with scissors (14), had a lost cap (4), had a cut bladder (4), had a torn strap (4), had a stabilization plate break (3), had a lost screw (2), had a rod locking clip break (2), or had a lost bulb (1). The most common source of limb injury that resulted in tourniquet use was penetrating trauma, and these wounds often included bone and soft tissue injuries.² As part of the care of these complex vascular and musculoskeletal wounds, devices were cut off to minimize handling of a fractured limb.

Every device had wear usually manifest as minor fraying, abrasions, or deformity about the band edge or bladder. Wear and tear, such as how much it was twisted and thereby stressed and deformed, indicated how the device was used. Substantial deformation in some cases led to breakage and thus ineffectiveness. Effectiveness was similar to prior reports (28 ineffective, 52 effective, and 79 unknown); unknown effectiveness most commonly occurred when casualties had multiple devices on multiple limbs but ineffectiveness in one limb could not be specifically assigned to one device unless it was

TABLE III. Ideal Emergency Tourniquet Traits With Practical Notes

Trait	Ideal	Practical Notes
Effective	Stops distal pulse	Stops distal wound bleeding
Use width	Wide compression	≥ 38 mm
Length	Fits casualties	Infant forearm, obese adult thigh anthropometry
Use ease	Simple to apply	Use with little to no training, not fiddly or fussy
Weight	Low carry weight	Practical, transportable; e.g., <230 g for a soldier
Tactical use	Care under fire	Danger, darkness or dimness, noise, distraction
Cost	Inexpensive	<\$25 for field device in bulk supply
Torque control	User can limit force	To prevent overtightening
Size	Small volume	Small carry cube configuration, no assembly
Application speed	Don quickly	Fast to apply, doff quickly; e.g., <60 s
Self-application	Casualty dons, doffs	To upper and lower extremities
Open-ended design	Can route proximal	Limb entrapped, splinted, externally fixed
Don single-handedly	Single-handed	Casualty can put on with a single hand
Toughness	Wears little in use	Hard to break, reusable, durable, waterproof
Doff emergently	Rapid removal	In emergency, best if scissors or knife unneeded
Stable	Stays effective	Does not slip on skin or release inadvertently
Mechanics	Internal capacity	Can gain effectiveness without huge user effort
Power	Twist or pump	Manual or foot-powered, not battery-powered
Placement	Stays put	No slipping on limb; single loop
Multisetting	Field to hospital	Injury site to ED to surgery
Replacement	Can don again	Placed back on without much work or time
Repair ease	Few repairs needed	Component replacement, easily tested forward
Cleaning ease	Washes quickly	Only soap and water needed, no disassembly
Storage cube	Stores densely	Comes assembled in small storage volume
Storage life	Shelf life >10 yr	Environmentally and heat-stable, no dry rot
Safety	Safe use limits	Pop-off valve, windlass break-off
Safe pressure	Manometer	Pressure measurable for safe threshold
Monitors	Pressure, timer	Safe manometry, overtightening detection
Conformity kept	Maintains shape	No expansion or stretch over time
Rugged materials	Field-ready	Austere: cold, hot, wet, sand, mud, ice, dust
User expectations	Preconceptions met	Device use concordant with user expectations

TABLE IV. Stewardship Tasks for a Hospital's Emergency Tourniquet Program

- Finding used tourniquets about the hospital
- Cleaning, testing, maintaining, repairing, and drying tourniquets
- Storing tourniquets for future use
- Prepositioning tourniquets at-the-ready in the ED
- Reordering tourniquets to maintain adequate supplies
- Recording tourniquet use for performance improvement survey
- Providing performance results to providers and trainers
- Providing feedback to manufacturers for tourniquet design refinement
- Educating new providers about tourniquets
- Coordinating among nurses and medics in operating rooms and the ED

labeled for that limb.² The three most common devices seen in this report were the same as in the prior report²:

- Combat Application Tourniquet (CAT), Composite Resources, Inc., Rock Hill, SC
- Special Operations Forces Tactical Tourniquet (SOFTT), Tactical Medical Solutions, Anderson, SC
- Emergency & Military Tourniquet (EMT), Delfi Medical Innovations, Vancouver, BC

Previously reported effectiveness rates of single EMTs (92%), CATs (79%), and SOFTTs (66%) were all different from each

other ($p < 0.002$).² Ineffectiveness was associated commonly with distal pulse persistence, occasionally with failed hemorrhage control, and rarely with breakage.

DISCUSSION

One-Handed Application is not Needed in the ED Setting

Many recovered devices were designed soon after the U.S. Army published requirements for candidate devices. These requirements included the ability to self-apply the tourniquet to an injured upper extremity and thus required one-handed application. This requirement significantly constrained designs and led to trade-offs in other functional traits. This requirement was developed in the absence of analysis on how frequently self-application was needed in the target population, but data from the Joint Theater Trauma System is now available.² Kragh et al. reported tourniquet use in 499 casualties, of whom 16 (3.2%) had tourniquets applied to both upper extremities. Bilateral injury can preclude one-handed application, which might decrease survival rates; but the survival rate for these 16 was 75% (12/16) vs. 87% (422/483) for those 483 casualties that did not have tourniquets on both upper extremities. This infrequent and small 12% disparity (75% vs. 87%) was not statistically significant ($p > 0.05$). One-handed application

TABLE V. Tourniquet Designs, Makers, and Maker Location

Design Name	Maker and Location	Devices Recovered	Devices Functional
CAT	Composite Resources, Rock Hill, SC	97	73
SOFTT	Tactical Medical Solutions, Anderson, SC	37	33
EMT	Delfi Medical Innovations, Vancouver, BC	13	2
Improvised tourniquets	Not Applicable	8	2
Ratcheting Medical Tourniquet (RMT)	M2, Winooski, VT	2	0
Self-Applied Tourniquet System	Marketing Tactics, LLC, Lake Worth, FL	1	0
LBT	London Bridge Trading, Virginia Beach, VA	1	0

in aid stations, ambulances, or EDs has not been reported. In sum, there was not a common need for one-handed tourniquet application, and there was no statistically significant survival disadvantage.

Device Effectiveness was Associated With Device Width and Limb Girth

To evaluate the appropriateness of device width, the investigators used an existing mathematical model to associate effectiveness with device width.⁵ Using anthropometric data from the target population, device widths, and the previously published relationship among width, limb circumference, and occlusion pressure, we characterized device effectiveness by limb size. The most challenging use of tourniquets is in the proximal thigh since it has such a large girth.² Recent U.S. male soldier proximal thigh circumference was 71.46 cm (28.13 inches) at the 99th percentile.⁴ Device effectiveness has been associated with limb artery occlusion pressure (P) and a ratio (R) of limb circumference to device width.⁵ An equation that fit the data was that $P = R \times 16.67 + 67$ for the relationship of limb artery occlusion pressure (P) to a ratio (R) of limb circumference to device width.⁵ The three most common devices seen in this study were the 25-mm-wide SOFTT, the 38-mm-wide CAT, and the 88-mm-wide EMT. Given a 71.46-cm thigh; the occlusion pressures for these devices were 543 mmHg (SOFTT), 380 mmHg (CAT), and 202 mmHg (EMT), which were unsafe, intermediate, and safe pressures, respectively.

CAT is the Standard Issue Device

The CAT (Fig. 1) was invented by military medics in an Afghanistan cave, the company that distributes it is run by former military medics, and the CAT is assembled in a sewing and assembly shop dedicated solely to this device. The CAT's effectiveness rate was the highest of the field tourniquets at 79%,² a rate in stopping compressible bleeding on the battlefield that a key tourniquet advocate, Colonel John B. Holcomb, asked for in 2002 as an "80% solution now instead of a 100% solution after we all retire."

The self-adhering band (an inner strap within a 38-mm-wide outer band) and stabilization plate upon which it was twisted had matching deformations that were proportional to each other in size but opposite in direction, which implied that the torque amplitude was associated with the degree of



FIGURE 1. Combat application tourniquet.

Photograph of the CAT (photograph used by permission of North American Rescue, Inc., Greer, SC). The CAT is a windlass and band design, a standard field tourniquet issued to deployed U.S. soldiers.

deformation. The inner strap had wear and tear where it contacted the windlass slot; the point of maximal stress within the fabric was at the point of maximal fabric deformation. The self-adhering band can be routed through the friction adaptor buckle in two ways. In one-handed application, it is routed through the distal opening only; whereas in two-handed application (and entrapped limb use), it is routed through both the proximal and the distal openings. Routing through both openings is indicated in lower extremity use also. In this second way, the self-adhering band is compressed (loop's side upon hook's side); this additional routing and compression added friction and security so that the band cannot be undone inadvertently. This double-routing also keeps the band from slipping when more torque is required in use on the thigh. During training, most applicators in training and care actually put the band in the one-handed routing inadvertently even when doing the two-handed application until corrected unless specifically forewarned.

CATs showed wear patterns which indicated that how the devices were used affected how the device performed. For

example, the inner strap folds went clockwise or counterclockwise depending on the direction of hand twisting of the windlass (plastic rod of glass-reinforced nylon with a chamfered slot passing the inner strap). More importantly, when the CAT was applied loosely (not enough slack was taken out) before windlass twisting began, too many twists of the windlass were needed ($>540^\circ$, one twist was 180°) to take in the slack before compressing the limb. Such loosely applied devices had to be overtwisted since hemorrhage was not controlled with fewer twists and the device rolled in the direction of twisting (Fig. 2). As roll progressed, the windlass and its slot became perpendicular to the pull of the inner strap instead of being parallel as it was before twisting. Roll then put the windlass at a structural and mechanical disadvantage as less than half of the windlass diameter resisted torque instead of the whole. This phenomenon was observed in care, and direct feedback for complying with the instructions to remove slack before twisting the windlass minimized roll and improved results. Noncompliance led to device deformation, breakage, and ineffectiveness. Most (63%, 61/97) CAT windlass rods had a craze, a fine crack, at the chamfered slot; and this undisplaced crack occurred only at one spot, ≤ 2.5 mm from the apex (Fig. 3). The crazes were seen as a fine, white-gray line originating at the slot apex and going outward; they originated adjacent to the site of the maximal inner strap deformation. Furthermore, in rare occasions, the inner strap tore before the windlass broke; and in these cases, there was no craze. Therefore, the windlass was the weakest component more often than the inner strap. In laboratory testing, a craze was caused to form with forceful torque and even to break the windlass. Several CATs that were

similarly damaged during training, familiarization, and informal assessments were also gathered. Breaks originated only at the craze. Discussions with the manufacturer indicated that the device engineers knew that the mechanical and structural properties are well beyond the clinical need of effective force and that the overtwisting in misuse might lead to breakage, which was a way to keep users from harming casualties inadvertently. These facts converge on the idea that overtwisted windlasses can be broken. This occurred rarely in clinical use but commonly in the laboratory when the slack was not taken out before twisting and overtwisting rolled the windlass slot perpendicular to the intended use.

EMT, the Most Common Hospital Device

The EMT (Fig. 4), designed and distributed by Delfi Medical Innovations (Vancouver, BC, Canada), was invented by a team led by James A. McEwen and made by a company with extensive organizational expertise in designing tourniquets for elective use in the operating room. The company is led by a clinical engineer, and the EMT is manufactured in a surgical tourniquet manufacturing facility with extensive quality control measures.

The EMT device is a pneumatic tourniquet that has a bladder that goes around the limb, a clamp that limits the inflated portion while holding the bladder close to the limb, and an inflator bulb with connector tube and twist cap. The bladder, 88 mm wide, has midpoint spot welds so that the cuff lies flat and wide on the skin and does not become torus shaped and roll down the limb. These features make it similar to a

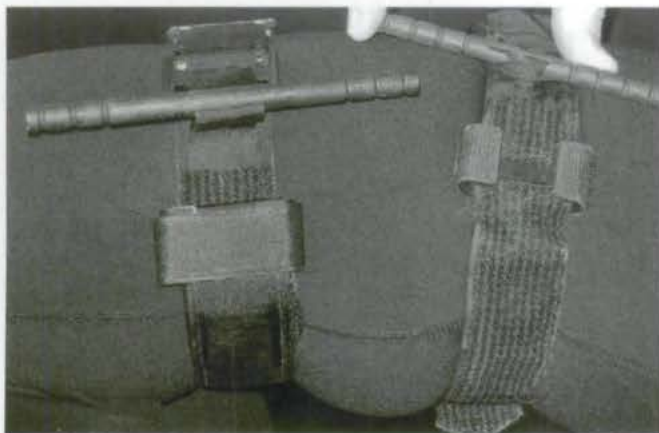


FIGURE 2. CATs before and after twisting.

Photograph of the CATs in a laboratory demonstration without (left) and with rod twisting (right). The left CAT band is perpendicular to the long axis of the limb, and all the slack was pulled out; the right CAT was perpendicular, but some slack remained before twisting. The twisting made the right CAT band yaw right (the top portion turned right) with right-handed twisting (applier's wrist supination). The right CAT has begun to roll (right) and pitch forward slightly in this process, and continued to do so when overtwisted in clinical use. As the inner strap twisted about the rod aperture, the outer, self-adhering band became redundant and bunched up as the limb was compressed so the strap folds became prominent.

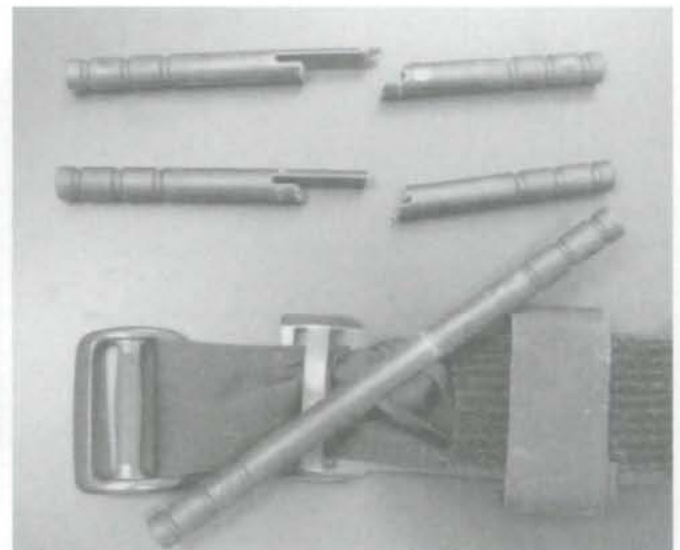


FIGURE 3. CAT after use and windlass pieces after breakage.

Photograph of a portion of a CAT below in the USAISR laboratory demonstrating the craze on the right side of the windlass aperture as a fine white line (with cross-striations along the materials microfibers). The craze is transverse to the rod and is underlaid by the edge of the inner strap. The CAT windlasses above are shown in pieces after a laboratory test demonstrating that the breakage began at the craze.



FIGURE 4. Emergency and military tourniquet. Photograph of EMT with bladder cuff, clamp, and bulb and connector. Note the white twist cap to open and release air or close and allow inflation (photograph used by permission of Delfi Medical Innovations, Vancouver, BC).

blood pressure cuff except for the clamp. The EMT clamp is precision-milled; has individual device serial numbers; and is designed for use in hospitals, clinics, or ambulances. The EMT is heavy, expensive, and delicate compared to the SOFTT and CAT. The 10 used EMTs (absent from the 159 devices) were collected after use, packaged, shipped across three continents, analyzed, and redesigned; then newly manufactured replacements were shipped back and used all this within 7 weeks of collection, an example of rapid spiral development.

In clinical use, the EMT performed well. The effectiveness rate of the EMT was the highest of all devices in clinical practice at 92%.² Field devices were often replaced by EMTs soon after arrival at the ED in the later two Baghdad studies.^{1,2} Cuff inflation yielded a scalloped limb compression pattern that was interesting but showed no problems (Fig. 5). Scalloping was most pronounced when the slack was not taken out before inflation, and this was analogous to the CAT issue above; all instructions emphasize removal of slack before tightening, yet slackers remain problematic. Recovered EMTs had wear patterns that were distinctly different from the other designs mostly because the EMT was the only pneumatic design. The bladder failed when cut (e.g., two knife holes on the inner and outer bladder lamina overlying each other after a scalpel blade fell on it directly under where emergency physicians performed lifesaving resuscitation procedures like catheter placement). Emergency physicians liked the performance of the EMTs but distrusted early versions because they wore out quickly or failed when damaged. Such damage was not commonly detected by users until testing was done regularly by the site program steward (Fig. 6). One benefit noted by users and testers was that the

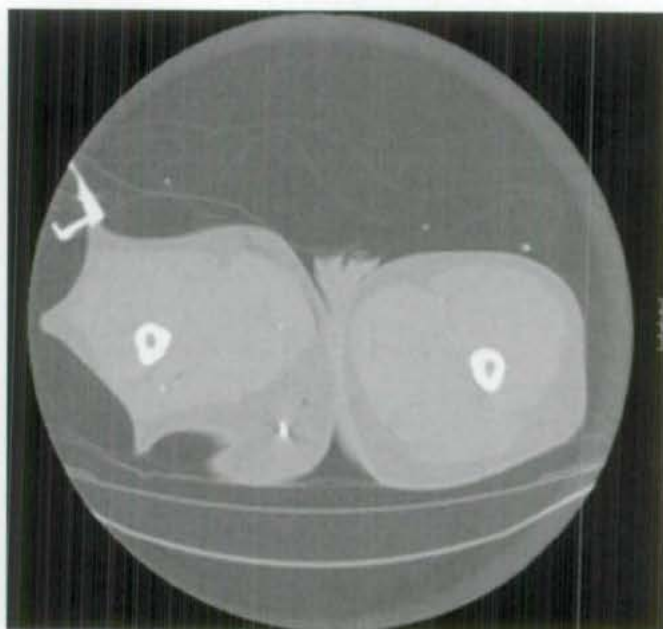


FIGURE 5. Computed tomography of a casualty thigh with a tourniquet. The image shows a cross-section of both proximal thighs. The normal left (reader's right) thigh is round, whereas the other thigh has been compressed by an EMT which indented the thigh because the EMT bladder has spot welds at which it does not inflate. These spots were designed to keep the EMT flat so it did not become like a bicycle inner tube and so roll distal on the limb. As the casualty's thigh axis is not collinear with the scanner, the tourniquet was not perpendicular to the scanner. Thus, it was on the lateral thigh with an air density signal within the bladder, but it was distal and out of plane medially.



FIGURE 6. EMT testing after clinical use. Photograph of inflated and submerged EMT leaking air bubbles from a bladder puncture. The bubbles are seen near the ulnar border of the ring finger tip. After this device was used well for a casualty, the bladder leaked during underwater testing. This EMT was a 2006 model, which led to a redesign of the bladder.

pneumatic device hurt casualties the least since the EMT was so wide and the inflation was gentle, whereas windlass twisting was jerky on fractured limbs.

Ratchet Tourniquet

The London Bridge tourniquet (LBT) is a band with a metal ratchet for maximum mechanical advantage that allows for quick one-handed application. Solid construction includes a narrow (25 mm) band of thick nylon webbing. The ratchet has thick steel alloy plates. The LBT is the heaviest field tourniquet (260 g) and has the most steel components. It is an extreme example of the powerful ratchet devices favored by a few elite U.S. Army Rangers. The device is similar to those used in securing heavy and large cargo items like bulky pallets to aircraft frames. Design-specific problems included sand-clogged ratchets. A casualty presented with an LBT proximal to a subtotal traumatic, transradial amputation. Hemorrhage was controlled by the device. The casualty had severe pain and had regional anesthesia in the ED before surgery (Fig. 7). Forces applied by the device can be extreme and painful. The device handles the limb as if it were cargo, a radical prioritization of life over limb in a black-white way as if effectiveness comes from superior force and that safety is no priority or too subtle to consider. By addressing a problem without fully understanding the consequences, ratchet device designers deprioritized limb safety while favoring mechanical action over thoughtful analysis, as if a simpler solution was best, as if best care had only one essential—force.

Improvised Tourniquets

Improvised tourniquet effectiveness was less than that of well-designed tourniquets but was better than not using a tourniquet at all.² Wide, improvised tourniquets were more effective than narrow ones (42% vs. 25%) in this report, which is similar to

the findings of the prior report.² Most improvised tourniquets were strap-and-stick constructs; others included a broad spectrum of strings, intravenous tubes, bungee cords, bands, waist belts, screwdrivers, scissors, tree limbs, and rifle cleaning rods (Fig. 8 and Table VI). In care, "There is little to no evidence that Afghan soldiers have improvised when needed to save a life. If the factory bandage or tourniquet isn't available, they



FIGURE 8. Improvised tourniquet.

Photograph of a casualty thigh with an improvised tourniquet used. A bandage scissor was used as a windlass and folded muslin cloth was a band. The hip is proximal and to the left of the overlaid ruler. Note that the band is less than 25 mm wide (one inch, photograph used by permission of John B. Holcomb, MD).



FIGURE 7. Forearm amputation with both a field and an operative tourniquet.

Photograph of a supine casualty forearm in an operating room before surgery. The head and torso are above and left, respectively and the subtotal transradial traumatic amputation is below right. The limb is on an arm table, and the LBT is proximal to the elbow flexor crease and overlies a remnant of the cutaway uniform sleeve. An operative pneumatic tourniquet system is proximal to the field tourniquet. One remnant of a tendon as seen is in the middle of the forearm transection and connects the hand to the forearm.

TABLE VI. Practical Guidance on Emergency Tourniquet Devices

- In this work, the best ambulance device was the EMT.
- In this work, the best field tourniquet was the CAT.
- Tourniquet design should account all relevant science, including casualty anthropometry.
- When user assumptions mismatch the device science, problems abound.
- When user assumptions match the device science, optimal care is more easily attained.
- Designs should meet user assumptions if scientifically grounded.
- Users should understand how devices work best to attain optimal outcomes.
- If one device does not stop the bleeding, then use a wider device or use two side-by-side.
- Different devices have different components that wear or break depending on use or misuse.
- Some desired traits (one-handed application, entrapment use) are not essential to common use.
- Specific devices are single-use or designed for reuse, and a steward should check devices.
- Leaders should select devices most appropriate for their users based on the best data available.
- Ideal device traits vary by care setting (e.g., field vs. ambulance).
- Use scientifically designed, laboratory tested, and clinically validated tourniquets.
- Use improvised windlass tourniquets when scientifically designed tourniquets are unavailable.
- Tourniquet education, training, and doctrine are vital and should be refined based on evidence.

let their wounded comrade go without."⁶ Conversely, at the same time, Iraqis improvised commonly with any imaginable material, whereas Afghans did not improvise although similar materials were available and they were exposed to the same U.S. doctrine as Iraqis. These facts indicated that there may be cultural assumptions affecting tourniquet use.

User Actions were Associated With Device Effectiveness

The findings of this study are important because actual device performance was associated with user actions and refinements in training on how to use these lifesaving tourniquets are indicated to improve care. First aid devices are rarely analyzed in such a way as here. How tourniquets work (i.e., pressure) is not how they work best (i.e., moderate pressure over a safe width).⁷ The pressure in or under the tourniquet is not the key to optimal use. The key to effectiveness is the arterial transmural pressure gradient, and a key to safety is limiting the gradient in the nerve because it is the tissue most vulnerable to gradients.^{8,9} Users often assumed that optimal use required more force, but optimal use is not synonymous with effective use; optimal use must include safe use. Although tourniquets are often preconceived as a simple 18th century technology, the clinical problems are complex, the science is subtle, and the facts are stubborn. Thus, there are scientific limits to practical use of tourniquets. If effectiveness is increased too much, safety is decreased; and if safety is increased too much, effectiveness is decreased. Safety and effectiveness are yin and yang—to be balanced. Although wide tourniquets are generally better than narrow ones, certain wounds are so proximal that the tourniquet can only be placed over the wound as opposed to 5 cm or so proximal to the wound. Making tourniquets wider would increase this problem—recently evidenced to be 1.7% of cases wherein the devices have partial effectiveness (4/232).² A refinement of tourniquet training and doctrine is needed to reflect these subtle facts.

The spectrum of device designers ranged from medics with operational military experience making simple, heavy devices in a garage from parachute rigging materials permitting high torque to clinical engineers with experience designing surgical instruments and making complex, delicate, precise, and costly devices supported by extensive evidence. In laboratory testing, the background of the device designer was associated with a successful device in that those who knew from experience how tourniquets were effective designed effective devices. However, those who understood how devices were both safe and effective designed devices that were both safe and effective.

A "more is better" assumption came from lay users in their spontaneous solution to a common and lethal problem when they started using more field tourniquets side-by-side to the first if the first failed to control hemorrhage. This fortunate finding led to higher effectiveness rates and a refinement in clinical guidelines.² Another "more is better" assumption led to the problem of the twist cap falling off after the plastic ridge at the end of the threads was overridden during stressful appli-

cation. A third "more is better" assumption was indicated in the initial special operations forces response to the need for better tourniquet designs in that there was first a search for a stronger dowel to withstand more torque while the science clearly indicated that there should have been a search for a wider band. When users know that width is the key to effectiveness (e.g., users in the Baghdad ED), effectiveness is easily and safely attained by using wide devices or using narrow ones side-by-side. When users emphasized finesse over force, optimal care resulted; force led to misuse.

Newly evidenced in the current report are assumptions of users that determine the use and resultant wear and tear of devices, the most obvious example being the "more is better" assumption, which had mixed results because of the scientific subtleties. For example, the side-by-side use worked well but for the unexpected reason of the complex relationship among device width, limb girth, and artery pressure. Multiple issues determine optimal use such as when devices are used, the manner of their use, and the types of injuries for which they are used; and all of these are recently evidenced to be essential in determining outcomes.^{1,2} By clarifying the details that affect outcomes, the current report focuses user attention to key details to avoid pitfalls and to attain optimal use.

User assumptions are rarely voiced until the user has a clinical failure and subsequently discusses it with an expert. Misconceptions then become clear; for example, the misconception that two-boned limb portions such as the forearm and leg risk ineffectiveness when actually effectiveness is high.² Device designs concordant with user assumptions can work well unless the assumptions are incompatible with established fact. Discovery of such incompatibilities yielded teachable moments; but when user assumptions were discordant with doctrine and training, then more teachable moments were needed to dispel misconceptions. User confidence in using tourniquets was U-shaped in that it was initially high before training; users did not grasp that tourniquets were tricky or that science was subtle. After they received training and experienced a few cases, users had a deeper understanding that the tourniquets were tools that required respect; and so their self-confidence dipped in disillusionment. With extensive experience, users learned to avoid pitfalls and fix problems on the fly for mass casualties, and confidence rose.

Survey Limitations and Future Directions

Limitations of this report are several. This work is an observation, not a controlled experiment. Although clinical and device data are linked, complete linkage was limited to some devices because of occasionally missing data. A significant challenge to educate users to the scientific subtleties persists in part because they desire simplicity; they want a cookbook recipe when a science report is due. For users without the time to sort and weigh grades and quantities of evidence, guidelines refined on the basis of new evidence are offered. It is not the place of tourniquet experts to tell users what device is right for them. For example, certain users, such as outfitters of

the military pilot survival kit, may radically reprioritize a trait like cube as more important than width since special needs differ from those in general use. However, such special selections require device-specific training and doctrine that are currently absent. Had the study been a scientific experiment, it would have allowed a better understanding of concepts; but the investigators could only survey actual use, which was useful for practical lessons learned.

Future research can take several directions. This work, to our knowledge, is novel by analyzing used first aid devices, and we aim in the future to improve collection of devices and data. Torque may be associated with under-tourniquet pressure. The number of twists may cause a steep increase in pressure when overtightening (risking breakage and nerve palsy). Band width may be associated with torque. The training for how tightly to pull the slack out before twisting currently specifies that no more than three fingers should be worked under the band; perhaps there is an ideal range of twist counts (e.g., three to six). Limb occlusion pressure varies more than systolic blood pressure,¹⁰ and the associations among effectiveness and casualty traits may be studied to tailor device use to individuals and not necessarily apply one strategy to all casualties.

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